Relativistic carcinotron with a thermionic injector of electrons

Article *in* IEEE Transactions on Plasma Science · July 1998

DOI: 10.1109/27.700762 · Source: IEEE Xplore

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Relativistic Carcinotron with a Thermionic Injector of Electrons

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***Abstract*—An experimental study directed to the determination of a mechanism for microwave breakdown in a relativistic X-band carcinotron is presented. An electron beam was generated using a thermionic cathode, which provided a stable beam geometry. The use of this cathode decreased the probability of breakdown caused by electron bombardment of the slow-wave structure.**

An important part played in microwave breakdown are molecules absorbed on the slow-wave structure surface. It is shown that the presence of these molecules, an implementation of conditions for secondary-electron resonant discharge (SERD), can result in a very fast (during 10–20 ns) limitation of the radiation pulsewidth.

To remove the adsorbed molecules, heat degassing of the slow-wave structure and a collector of electrons was applied, going on continuously, during a working day of the device. By degassing and choice of slow-wave structure material, output radiation power of the device was increased by a factor of ten (up to 5 MW at the pulsewidth of 10 μs).

***Index Terms*—Heat degassing, microwave breakdown, relativistic carcinotron, secondary electron resonant discharge (SERD), slow-wave structure.**

I. Introduction

MICROWAVE breakdown is one of the principal factors that limit the power and pulsewidth of output radiation of powerful microwave devices [1], [2]. It is obvious that devices with the least electric field on the slow-wave structure walls, with other parameters being equal, are the most resistant to microwave breakdown. From this viewpoint, Cherenkov-type devices with smoothly corrugated slow-wave structures sized to the order of one radiation wavelength across or greater have a good chance of avoiding breakdown.

However, we do not succeed in realizing these qualities in full measure at present. As is known, the microwave breakdown is not determined by electric field entirely, but it may be initiated by charged particles (of an electron beam [3] and of collector and cathode plasmas [4]), a secondary electron resonant discharge (SERD) [5], [6], and field emission [7]. The initiation threshold depends on the surface and vacuum conditions.

Manuscript received August 11, 1997; revised January 23, 1998. This paper was presented in part at the International Workshop on High Power Microwave Generation and Pulse Shortening, Edinburgh, U.K., June 1997. This work was supported by the Russian Foundation of Fundamental Research, Grant 94-02-05511.

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Publisher Item Identifier S 0093-3813(98)04390-2.

One of the most well-studied Cherenkov-type microwave devices, the relativistic backward-wave oscillator (RBWO) or carcinotron, was investigated with a relativistic electron beam (REB), generated using a thermionic injector (showing the stable geometry of an electron beam and the absence of cathode plasma) and with a relatively low level of the output radiation power. Influence of the slow-wave structure surface condition on the RBWO characteristics has been studied as well. The results are presented in this paper.

II. Identification of the Factors that Initiate Microwave Breakdown

The first microwave experiments that were carried out with a thermionic electron injector [8] showed that the stability of the REB cross structure was not yet sufficient for the production of microwave pulses of large duration. In the RBWO, even at the minimum stable level of output power, which was 0.5 MW, and corresponding fields on the wall were 60 kV/cm, the pulsewidth did not exceed 0.5–0.7 μs. Residual pressure equaled to $5 \cdot 10^{-7}$ torr using an oil-free vacuum system. Microwave pulses were accompanied by vacuum deterioration that led sometimes to electron gun breakdowns.

The initiation of microwave breakdown at such low fields and small pulse energy may be explained, in principle, by the important role played by the coating of adsorbed molecules [9] on the oscillator walls. The desorption and ionization of these molecules occur by means of the surface bombardment with charged particles. These particles may be originated from a REB, field emission, and SERD.

The absence of bombardment with charged particles was tested by the direct measurement of current in the slow-wave structure circuit with 0.01-A sensitivity. Field emission does not play an important part at such fields and only generates the priming electrons for SERD. Only at fields of several hundreds kV/cm does this process become independent as a factor of microwave breakdown initiation [7].

Thus, SERD remains a real threat for microwave device operation. However, a complex combination of high-frequency and quasistatic fields in the neighborhood of the waveguide corrugated wall and possible temporal dispersion of secondary electrons [10] does not allow us to obtain a simple explanation for the initiation of SERD. In order to study the possibility of this discharge beginning and to find out its ability to initiate microwave breakdown, it is reasonable to perform the modeling experiment with the same vacuum conditions and with the configuration of walls and fields being simplified.

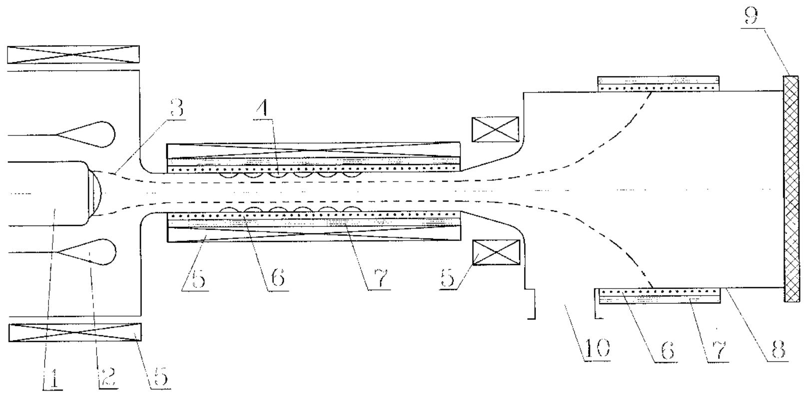

Fig. 1. Experimental setup with a local area of heat degassing: 1: cathode, 2: intermediate anode, 3: tubular electron beam, 4: slow-wave structure of a microwave device, 5: solenoid and coils, 6: heaters, 7: heat screens and water jacket, 8: collector, 9: quartz vacuum window, and 10: evacuation pipe.

Microwave fields, vacuum conditions, production technology, and material of an original RBWO slow-wave structure were modeled in the experiment. The 10-μs radiation pulse from a magnetron with frequency of 9.1 GHz were brought to a rectangular waveguide 23 $\times$ 10 mm^2 across narrowing smoothly to 23 $\times$ 2 mm^2. The corresponding microwave fields on a waveguide wall reached 45 kV/cm. The waveguide was made of copper by the electrochemical growth method.

The breakdown in the waveguide occurred at the microwave fields of 23.5 kV/cm. According to estimation [5], this value corresponds to the calculated field of the SERD initiation, that is, more exactly, the lowest-electric-field mode of the so-called two-sided SERD. When the longitudinal magnetic field of 1.6 kOe was applied, the breakdown in the waveguide occurred at 10 kV/cm, which corresponded to the calculated field of the cross-field, one-sided SERD beginning [5]. The further increase of magnetron power resulted in a sharp decrease of the breakdown delay time that did not exceed 10–20 ns at the extreme fields.

After heating the waveguide to 400 °C, at which the adsorbed molecules is known to be essentially removed [9], breakdowns in the waveguide stopped to occur in the whole range of realized microwave fields. Cooling of the waveguide to room temperature resulted in restoration of the former level of breakdown microwave fields.

III. Experiments with the RBWO that Has a Degassed Slow-Wave Structure

The results of the modeling experiment showed that the vacuum conditions in question were an important factor for SERD. Furthermore, these results convinced us that it is necessary to remove the adsorbed molecules from the surface of a slow-wave structure to increase its breakdown strength. For this purpose, a local area of heat degassing, including the slow-wave structure of a microwave device and the collector of an electron beam, was set up in the accelerator volume [8] (Fig. 1). By means of two special heaters (their powers were 2.5 and 1.4 kW, respectively), the temperature of the slow-wave structure and the collector was increased up to 700 and 600 °C, respectively. Evacuation of this area with a supplementary cryogetter pump provided residual pressure of the order of 10^{-8} torr, whereas pressure in the electron gun area was $5 \cdot 10^{-7}$ torr.

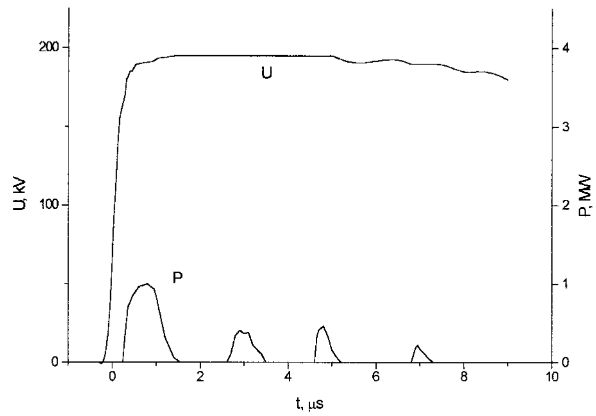

Fig. 2. One of the first pulse of operation at the regime near the self-excitation threshold: $U(t)$: accelerating voltage and $P(t)$: microwave power.

The slow-wave structure of the microwave device (which was an RBWO) was produced of oxygen-free copper, and its inner surface was polished. The collector section was made of the same material.

The experiments showed the efficiency of the technological advances made. After 6 h of heating, just in the first electron beam pulses, the series of microwave pulses began to appear (Fig. 2), whereas in the preliminary experiments oscillations stopped with the first pulse. The corresponding microwave power slightly exceeded the start threshold and amounted to 0.5 MW.

After 40–50 conditioning pulses, radiation pulsewidth came close to duration of a high-voltage flat top, which was near 8 μs (Fig. 3). Radiation pulse energy (measured by a calorimeter similar to the one described in [11], but with an enlarged aperture) reached 50 J at a power of 5 MW and efficiency of 11%, and the corresponding electric field on the wall was 200 kV/cm. A further increase of the electron beam power, over 50 MW, was accompanied by a radiation power decrease, whereas pulsewidth was the same (Figs. 3 and 4). Furthermore, no change of residual pressure was observed during the pulse. The experimental dependence presented in Fig. 4 may be explained by influence of the nonsynchronous

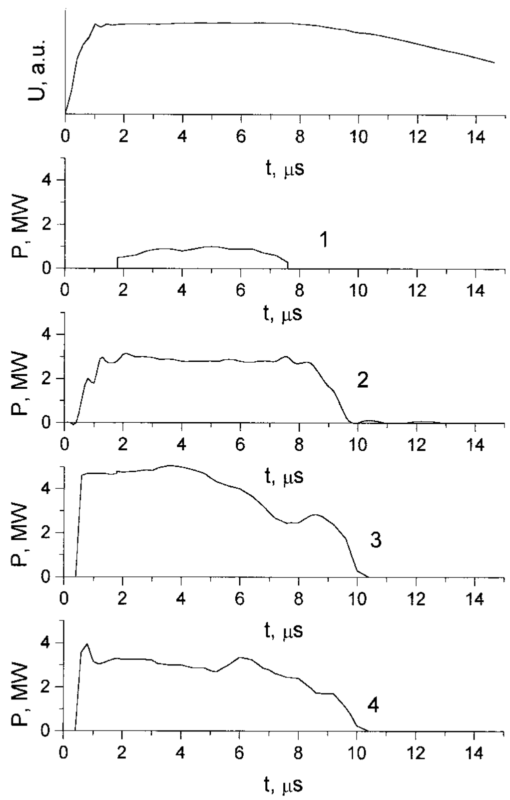

Fig. 3. Oscillograms of BWO microwave pulses at different voltage after the training period: 1: 204 kV, 2: 215 kV, 3: 230 kV, and 4: 260 kV.

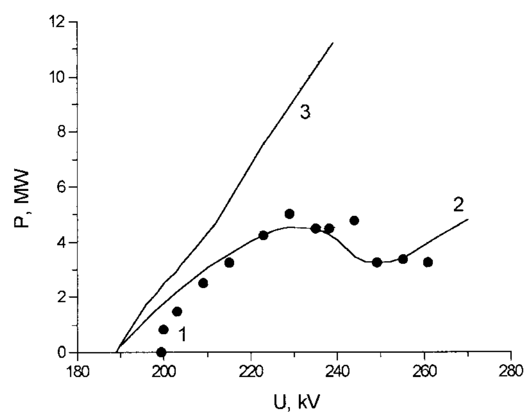

Fig. 4. Output power P as a function of accelerating voltage U: 1: experiment, 2: corresponding calculation by the "KARAT" code, and 3: calculation for the oscillator with a cathode-direction output.

following wave reflected from the cutoff narrowing on the energy-exchange process [12]. Computer simulations using the code "KARAT" of Tarakanov (see Fig. 4) confirms this possibility. As a comparison, the similar dependence for the RBWO with the cathode-direction output received by the same code is presented in Fig. 4. In the latter case, the following wave is absent.

It is also possible that the beginning of new modes of SERD with large discharge currents makes some wave absorption and has an influence on the above-mentioned dependence (Fig. 4). The evaluations made and the presence of erosion spots on the corrugation slopes do not conflict with this assumption.

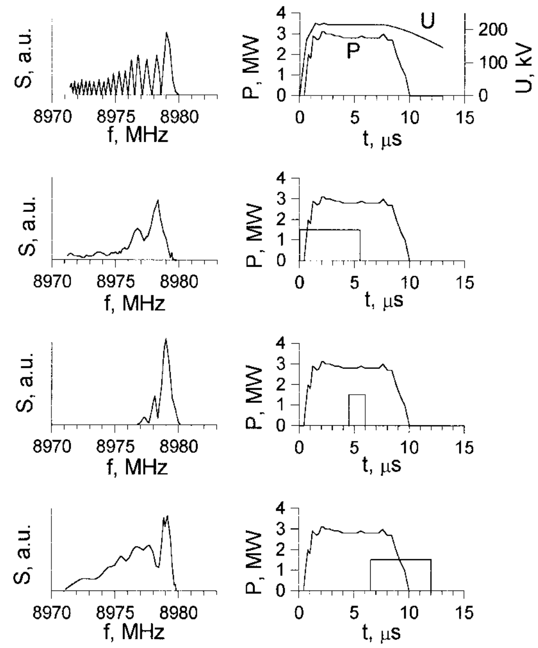

Fig. 5. Spectra of full microwave pulse $P(t)$ and of its forward, middle, and back parts. $U(t)$ is the oscillogram of voltage.

The oscillator reserved its abilities in producing long pulses during several hours after cooling of its slow-wave structure to the room temperature. However, after staying in the cooled-off condition and under residual pressure 10^5 torr for more than 10 h, the oscillator produced radiation with pulsewidth of no more than 0.5 μs and stayed in this position even after restoration of the nominal pressure of 10^{-8} torr.

The data about device operation may be complemented by the results of spectrum measurements, which reflect both the stability of the REB spatio-temporal characteristics and the absence or the presence of plasma that appears during the microwave breakdown. In an RBWO, these factors lead in particular to the widening of the radiation spectrum. The measurements were made using a spectrum analyzer. A typical picture of spectrum at power of 3 MW, when electron RF discharge does not arise, is shown in Fig. 5. Width and periodicity of the spectrum are in agreement with the theoretical insight about radiation frequency change, depending on energy of electrons during the high-voltage pulse (1.5 MHz/kV). The gating in the analyzer permitted us to receive the spectra of different parts of a pulse (Fig. 5). Spectrum width of the part that corresponded to the flat top of a voltage pulse was close to the natural value.

It is necessary to note that the local area of heat degassing was also used in the study of the RBWO with the slow-wave structure made of copper by the electrochemical growth method. Its extreme output power did not exceed 1 MW, and attempts to increase it resulted in sharp decrease of pulsewidth. Pores and impurities of the material do not apparently accommodate the necessary cleanness of the corrugated waveguide surface.

In order to suppress SERD, one version of RBWO slow-wave structures has been produced using titanium, that is, the material with the antidynatron property. By its geometry

and production technology, this oscillator was a copy of the above-mentioned RBWO made of oxygen-free copper.

Experiments showed that in the cold condition the titanium oscillator, like the previous one, was able to produce only short pulses of pulsewidth $\cong$0.5 μs. Heating up to 700 °C resulted in making of radiation power $\cong$ 1.5 MW at pulsewidth close to REB duration. An attempt to increase radiation power resulted in a sharp decrease of pulsewidth.

In contrast to the oxygen-free copper oscillator, the titanium device after cooling was not able to produce the pulses of full duration. In particular, after cooling to 200 °C, the pulsewidth decreased to $\cong$0.5 μs. The worse breakdown strength of the titanium oscillator may be explained by insufficiently high cleanness of the material or by insufficiently high vacuum for this well-absorbing material.

IV. Conclusions

Thus, the performed research confirms good prospects of relativistic Cherenkov-type devices as sources of multimegawatt, multimicrosecond pulses of coherent microwave radiation, when using vacuum technology close to that existing in industrial manufacture of vacuum devices.

The described method can apparently be applied at the regime of shorter pulses in the systems with field-emission electron injectors as well.

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Nikolay I. Zaitsev, for a photograph and biography, see this issue, p. 251.